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EXPERIMENTAL STUDIES IN SOLID STATE AND LOW TEMPERATURE PHYSICS--ETC(U)  
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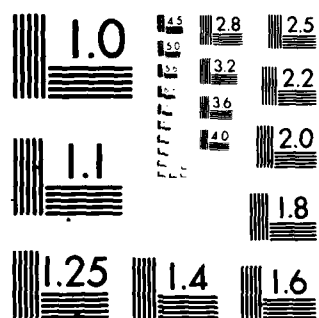
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(6) EXPERIMENTAL STUDIES IN SOLID STATE AND  
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# ABSTRACT

Experimental and theoretical investigations have been carried out in a broad area of low temperature and solid state physics which includes superconductivity, and magnetism in metals. The work in superconductivity has involved investigations of the Josephson effect, studies of the pair-field susceptibility of superconductors and investigations of the thermodynamics of the superconducting phase transition. The competition between the metal-nonmetal transition and superconductivity has also been studied in random metal-rare gas systems. In the area of magnetism, magnetically ordered materials and dilute magnetic alloys have been investigated. Enhanced hyperfine nuclear magnetic ordering was discovered in  $\text{PrCu}_6$  at about 2.5 mK.

The ONR contributed to the support of this work by supplying helium gas which was used to make up losses in the helium recovery operation associated with the use of liquid helium by the workers named in the proposal.

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## I. INTRODUCTION

The work described in this report consists of various experimental investigations in a broad area which has been called solid-state and low-temperature physics and which is now called condensed matter physics. The research was under the direction of Professors A. M. Goldman and W. V. Weyhmann at the School of Physics and Astronomy of the University of Minnesota and was supported under contract N00014-76-C-1086.

The scientific scope of the program was quite broad with investigations concerning superconductivity and magnetism in metals. Although these various areas of research are quite diverse, they are closely related from several points of view. In the first place, most of the properties under investigation are essentially macroscopic manifestations of quantum mechanics. Secondly, the systems exhibit transition to phases in which long-range order appears.

## II. DESCRIPTION OF RESEARCH

### A. SUPERCONDUCTIVITY

(Professor A. M. Goldman)

During the course of the contract, work in this area has been concentrated on a number of fundamental problems in three general areas. There have been contributions to the understanding of the Josephson Effect and to the development of the study of the pair-field susceptibility as a probe of the dynamics of superconductors. There have also been a number of investigations of superconducting fluctuations and the critical behavior of superconductors. Finally the competition between disorder related metal-nonmetal transitions and superconductivity has been probed in a series of investigations of the electrical properties of random metal-rare gas solids. In the following a brief account of the most important results of this research will be given.

#### 1. Experiments Relating to the Josephson Effect and the Pair-Field Susceptibility.

The work in this area evolved from studies of the Josephson effect in the mid 1960's. The early efforts involved the study of the I-V characteristics of strongly-coupled Josephson junctions, which exhibited a crossover from a Meissner state to a vortex state at a particular value of the magnetic field applied in the plane.<sup>1</sup> This work stimulated the definitive theoretical calculations of Owen and Scalapino.<sup>2</sup>

In this same period fluctuation rounding of the dc Josephson current was studied.<sup>3</sup> The calculations of Ambegaokar and Halperin resulted from efforts to understand the fluctuation-rounded I-V characteristics of planar

Josephson tunneling junctions observed in this laboratory.<sup>4</sup>

The focus of the work in superconductivity then shifted to studies of the generalized susceptibility or pair-field susceptibility of superconductors.<sup>5</sup> The latter is a quantity proportional to an excess current in the I-V characteristic of an asymmetric tunneling junction where one electrode is the superconductor of interest and the other one a metal with a higher  $T_c$ . During the course of the contract, the possibility of measuring the susceptibility was demonstrated using Sn-Pb junctions.<sup>6</sup> Quantitative studies were carried out using Pb-Al junctions and it was demonstrated experimentally that the susceptibility could be observed in the superconducting as well as the normal state of the electrode of interest.<sup>7</sup> When this was done, a propagating branch or charge imbalance wave was discovered. The theoretical explanation of this mode, now known as the Carlson-Goldman mode, required detailed consideration of the interaction of the disequilibria of the pairs, quasiparticles and phonons in the superconducting system.<sup>7</sup>

Recent studies of the pair-field susceptibility have been concerned with the effects of magnetic impurities on the dynamics of the order parameter, mode-softening of a superconductor in a current-carrying state, and the pair-field susceptibility of Cooper-limit proximity sandwiches.<sup>8</sup>

## 2. Superconducting Fluctuations and the Critical Behavior of Superconductors

The original thrust of this work was the study of dimensionality-crossover effects which were observed in NbN thin films with short coherence lengths.<sup>9</sup> The focus then shifted to studies of heat capacities of superconducting films. The technique of using the resistive transition of a



film as a thermometer was used to make qualitative measurements of heat capacities of Al films near their transitions.<sup>10</sup> Quantitative studies of amorphous-Nb<sub>3</sub>Ge films were then carried out using Au(Fe)-Cu thermocouple thermometers and ultra-thin sapphire substrates. In this work, a broad peak in the heat capacity was observed just below the BCS transition.<sup>11</sup> The temperature-dependent resistance was also compared with several theories which predict flux-flow resistance below the BCS transition temperature due to thermally excited vortex pairs. Although the transition is broadly consistent with such a model, no feature in R(T) was found that would imply a divergence in the conductivity that might be associated with a topological phase transition. The question probed in this work, that of the existence of topological phase transitions in 2-D systems has attracted significant experimental and theoretical attention in recent years.<sup>12</sup>

### 3. Electrical Conductivity and Superconductivity in Random Metal-Gas Solids

Metal-gas solids are made by co-depositing metal vapor and gas onto a substrate cooled to low temperatures. Films of Na and NH<sub>3</sub>,<sup>13</sup> Na and Ar<sup>14</sup> and Hg and Xe<sup>15</sup> have been prepared using a special molecular beam oven source in which the gases are mixed at high temperatures and then projected onto a surface held at 4 K.

The focus of the work has been the study of the composition dependence of the metal-nonmetal transition in the case of Na/NH<sub>3</sub> and Na/Ar films and on the competition between the superconducting transition and the metal-nonmetal transition in the case of the Hg/Xe films. In the Na/NH<sub>3</sub> system, the conductivity was found to be a nonmonotonic function of composition, a result which may be explained by what is known as polychromatic percolation.

In the Hg-Xe system, the conductivity as a function of composition appears consistent with microscopic percolation, at which point it crosses over to a regime with a negative temperature coefficient of resistance. In this regime the superconducting transition temperature drops rapidly. The fall of  $T_c$  with increasing insulator concentration may be explainable by a superconducting generalization of the random X-Y model.<sup>16</sup>

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## B. EXPERIMENTAL STUDIES OF MAGNETIC SYSTEMS

(Professor W. V. Weyhmann)

During the course of this contract, several fundamental contributions to our understanding of magnetic properties of materials have been made. In the earlier years this research concentrated on the collective properties of magnetically ordered systems and as time progressed the emphasis shifted to the very low temperature, very weak magnetic properties of dilute magnetic and nuclear magnetic systems. Below we shall highlight the three most important phases of this work.

### 1. Magnetically Ordered Materials

The discovery that spin reorientation is in some cases a second order phase transition was the thesis work of R. W. Houghton<sup>1</sup> and the interpretation of this result was provided by H. Horner and C. M. Varma,<sup>2</sup> working at the time at Minnesota on this contract (with Professor Nosanow). The experimental signature of the phase transition was the disappearance of the quadrupole modulation of the nmr spin echo signal, which was interpreted as indicating a fluctuation in the direction of the magnetization. The classical (Landau) theory of the transition predicted a double step (up and then down as temperature increased) in the magnetic contribution to the heat capacity, the steps occurring at the two endpoints of the rotation of the magnetization. This form of the heat capacity was confirmed in an experiment Weyhmann performed in collaboration with G. Sjolander and Prof. M. Moldover.<sup>3</sup> While the sharpness of the steps is not yet established, this is one of the few cases (the superconducting transition is another) in which the classical Landau behavior is observed and the only one in which two back-to-back second order transitions are intrinsic to the process.

## 2. Dilute Magnetic Alloys

The magnetization of dilute magnetic impurities in nonmagnetic, metallic hosts has been an important part of our work for several years. Holliday and Weyhmann<sup>4</sup> showed that Co in Au has a surprisingly large Knight shift and J. Babcock et al.<sup>5</sup> showed that Mn in Al remains nonmagnetic at very low temperatures. Another aspect of the work on dilute systems has been the precision measurement of the magnetic saturation behavior of Mn in Cu and Ag, most notably by D. Bakalyar et al.<sup>6</sup> To the best of our knowledge, this is the only extensive and precise determination of the saturation of a Kondo system in a high magnetic field. All of this work was carried on using nuclear orientation at temperatures between 8 and 30 mK.

## 3. Enhanced Hyperfine Nuclear Magnetic Ordering

In order to continue these studies at still lower temperatures and to broaden the spectrum of orientation studies that can be pursued, we began an investigation of the magnetic properties of enhanced hyperfine nuclear coolants, particularly PrCu<sub>6</sub>. Recently we observed the nuclear ordering transition in PrCu<sub>6</sub> at about 2.5 mK, measuring the magnetization and heat capacity behavior in magnetic fields.<sup>7</sup> Over the last few months we have observed anomalies in the electrical impedance of a small rod of this material and have noticed what appears to be a second phase transition at very low fields (less than 10 Oe) and slightly higher temperature.<sup>8</sup> This work opens the door to intensive investigation of the nuclear ordered state in metals where complete thermal equilibrium can be achieved (as opposed to <sup>3</sup>He or dipole-dipole ordering in metals such as Cu).

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